Special Report 83-24

August 1983

US Army Corps of Engineers

Cold Regions Research & Engineering Laboratory

Current procedures for forecasting aviation icing

A review

W.B. Tucker III

Prepared for
OFFICE OF THE CHIEF OF ENGINEERS
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Unclassified

SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER
Special Report 83-24

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE *(and Subtitle)*
CURRENT PROCEDURES FOR FORECASTING AVIATION ICING

5. TYPE OF REPORT & PERIOD COVERED

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
W.B. Tucker III

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
U.S. Army Cold Regions Research and Engineering Laboratory
Hanover, New Hampshire 03755

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
DA Proj. 4A161102AT24, Sci. Area C, Sci. Effort 01, Work Unit 006

11. CONTROLLING OFFICE NAME AND ADDRESS
Office of the Chief of Engineers
Washington, D.C. 20314

12. REPORT DATE
August 1983

13. NUMBER OF PAGES
34

14. MONITORING AGENCY NAME & ADDRESS*(if different from Controlling Office)*

15. SECURITY CLASS. *(of this report)*
Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT *(of this Report)*

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT *(of the abstract entered in Block 20, if different from Report)*

18. SUPPLEMENTARY NOTES

19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*
Aircraft icing
Meteorological phenomena
Meteorology
Weather forecasting

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

The responsibilities for aircraft icing forecasts in the U.S. lie with the National Weather Service (NWS) for civilian operations and the U.S. Air Force Air Weather Service (AWS) and Naval Weather Service for military operations. Forecasting technology is based upon empirical rules and techniques that were developed in the 1950s. The AWS is the only forecasting agency which issues explicit numerical icing products to aid the forecaster. These products are also based upon the application of techniques developed long ago. The NWS has

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SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

20. Abstract (cont'd)

no rigorous guidelines for developing icing forecasts, thus individual forecasters adopt their own preferred methods. The tendency is generally to "over-forecast," that is, to forecast too large an area of icing for too long a time. A major shortcoming in the ability to produce more accurate forecasts is that atmospheric parameters critical to icing are not routinely observed.

PREFACE

This report was prepared by W.B. Tucker III, Geologist, Snow and Ice Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. The work was performed as part of DA Project 4A161102AT24, Research in Snow, Ice and Frozen Ground; Scientific Area C, Research in Terrain and Climatic Constraints; Scientific Effort 01, Cold Environmental Factors; Work Unit 006, Icing Meteorology.

Technical review of the report was performed by L. David Minsk and Stephen Ackley of CRREL. The author is also grateful for reviews and valuable comments by Dave Dilley, National Weather Service forecaster at Logan Airport, Boston, Dr. Richard Jeck of the Naval Research Laboratory and SSGT Goodman and other personnel of the Air Force Global Weather Central.

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A REVIEW

W.B. Tucker III

INTRODUCTION

In-flight accumulation of ice on airframe and power plant components can drastically alter aircraft performance, sometimes with catastrophic results. For many of today's aircraft, icing is not a significant problem because they operate at high altitudes and pass through icing-prone layers only for a short time when climbing or descending. But a serious hazard is posed for fixed-wing, propeller-driven aircraft and helicopters that operate at altitudes of less than 25,000 ft, where icing is prevalent. Both the number of these latter aircraft and the number of hours they operate under instrument flight rules (IFR) are increasing. Most of them have little or no anti-icing equipment because of its cost and the sacrifice in payload that it requires. Fortunately, icing-related accidents are rare, primarily because pilots of under-equipped aircraft generally avoid forecast icing conditions. Those that do occur, however, are frequently fatal, due to the serious adverse effects that ice accumulation has on aircraft performance. A review of icing-related accident statistics is presented in a recent report on icing issued by the National Transportation Safety Board (NTSB 1981).

Federal Aviation Regulations (FAR's) prohibit flight into known icing conditions unless it has been demonstrated that the aircraft can operate safely under these conditions. The standards for demonstrating this capability are set forth in FAR Part 25, Appendix C. Early work by Jones and Lewis (1949) resulted in the development of two icing "envelopes" defined by liquid water content, droplet size distribution, and temperature. One envelope supposedly represents clear icing that would be encountered in cumuliform clouds, while the other defines rime icing conditions presumably occurring in stratiform clouds. Before being certified for flight in icing conditions, an aircraft must prove that it can be safely operated within the ranges defined by these envelopes. Recently, criticism has been expressed regarding the validity of the envelopes and other regulations concerning certification (Newton 1977, Jeck 1980, Horne 1981, NTSB 1981). The Federal Aviation Administration (FAA), along with the National Aeronautics and Space Administration (NASA) and the Department of Defense (DOD), are currently reexamining the standards outlined in FAR Part 25, Appendix C, with the intent

Table I. Definitions of icing intensity established by the Subcommittee for Aviation Meteorological Services of the Federal Coordinator for Meteorological Services and Supporting Research.

Trace of icing. Icing becomes perceptible. The rate of accumulation is slightly greater than the rate of sublimation. It is not hazardous even though deicing/anti-icing equipment is not utilized, unless encountered for an extended period of time--over one hour.

Light icing. The rate of accumulation may create a problem if flight is prolonged in this environment over one hour. Occasional use of deicing/ anti-icing equipment removes/prevents accumulation. It does not present a problem if the deicing/anti-icing equipment is used.

Moderate icing. The rate of accumulation is such that even short encounters become potentially hazardous and use of deicing/anti-icing equipment or diversion is necessary.

Severe icing. The rate of accumulation is such that deicing/anti-icing equipment fails to reduce or control the hazard. Immediate diversion is necessary.

of updating them. Based upon a recent compilation and detailed analysis of very old (about 1950) and very recent (Jeck 1983) aircraft icing research flight data, new envelopes characterizing supercooled clouds below 10,000 ft (Masters 1983) have been proposed.

Icing forecasts must allow those piloting aircraft with no anti-icing capability to avoid icing conditions. In addition, those in aircraft that are capable of flight in icing conditions need to know the intensity of any icing likely to be encountered, as there is a limit to the rate of ice accumulation that even the most advanced anti-icing systems can cope with. To define icing intensity, the Subcommittee for Aviation Meteorological Services of the Federal Coordinator for Meteorological Services and Supporting Research in 1968 adopted the following terms: trace, light, moderate, and severe. These terms are defined in Table I. Obviously, these definitions must be interpreted in light of the type of aircraft encountering the icing because the rate of ice accumulation depends on airframe component geometry and airspeed as well as on the atmospheric icing potential. This inadequacy has been pointed out in recent reports (Newton 1977, NTSB 1981). Both civilian and military forecasting agencies use these definitions of intensity, however.

Icing forecasts are prepared by the National Weather Service, the Air Weather Service of the U.S. Air Force, and the Naval Weather Service of the U.S. Navy. The general feeling is that most icing forecasts are very conservative --

that is, a larger area of icing is forecast than actually occurs in the atmosphere (NTSB 1981). The difficulty in forecasting icing arises partially because there are very few observations. In addition, observations of parameters which are essential to accurate icing forecasts are nonexistent (for example liquid water content and drop size distribution). Even measurments of temperature and relative humidity are made on too coarse a scale to permit refinement of forecasts.

This report reviews current icing forecasting procedures used in the military and civilian communities. No attempt at improving forecasting is made here; rather the idea is to present the current techniques and briefly explain their physical basis where possible. This compilation may provide a reasonable starting place when future efforts to upgrade forecasting procedures are undertaken.

A problem which quickly became obvious when this information was being compiled is that one of the key elements in forecasting icing is the experience and ability of the forecaster. As in all meteorological forecasting, personal experience is essential to the rapid production of a reasonable forecast. Individual forecasters may have "favorite" rules or techniques they use to produce an icing forecast. Because very few forecasting facilities were visited, few of these personal preferences will be presented here. Only those rules-of-thumb and forecasting techniques which had been previously documented or which were discovered during my few visits can be discussed.

AIRCRAFT ICING

Three kinds of ice can build up on an aircraft -- frost, rime and clear. Frost results from the direct sublimation of water vapor onto a surface in the form of ice crystals. This type of icing is not normally considered a serious in-flight hazard and will not be dealt with here.

Water droplets can exist in the atmosphere at temperatures as low as -40°C (AWS/TR-80/001). The freezing temperature of these supercooled droplets is raised when their internal stability is destroyed by impact with a foreign object. Rime ice is caused by the instantaneous freezing of small supercooled droplets. As a result of rapid freezing, the frozen droplets retain their spherical shape, and air becomes trapped between them. This gives the accumulation a rough, whitish, opaque appearance, and "fingers" of ice occasionally protrude from it. The shape of airfoils can be seriously distorted by rime accumulations.

Clear ice is formed when larger supercooled water droplets impact on an aircraft and spread before freezing. No air is trapped, and a smooth, clear glaze

build-up accumulates. This type of icing is very hazardous because it is the densest form of ice accumulation and adds significant weight to the aircraft, and because it accumulates very rapidly.

The requirements for icing, then, are adequate moisture (clouds) in the form of supercooled water droplets and below-freezing airframe temperatures. The type and intensity of icing depend upon the droplet size distribution, the number of drops present (liquid water content or LWC), and the collection efficiency of the accreting surface. Aircraft speed is also important because both the collection efficiency and aerodynamic heating, which acts to retard ice accumulation, vary with airspeed. These effects have been discussed in detail by Jones (1961) and Ryder (1978).

Clear ice is generally associated with cumuliform clouds. The large vertical air velocities in these clouds support higher concentrations of drops with larger diameters. The upward movement also carries warmer air, which is more conducive to clear ice formation. The FAR Part 25, Appendix C envelope for cumuliform clouds specifies an effective droplet diameter (or median diameter) range of 15 to 50 μm and a liquid water content range of 0.2 to 2.7 g m^{-3}. The temperature range extends from 0° to -22°C but it is unlikely that clear ice would form below -9°C (AWS/TR-80/001) except in situations like lee of Great Lakes convective snow squalls where temperatures could be as low as -10°C to -13°C (Dilley, pers. comm.). The consideration of freezing rain, which can cause severe clear icing, could extend the droplet size to over 1000 μm. Recent measurements (Glass and Grantham 1981, Bain and Gayet 1982, Gayet and Bain 1982) have verified that the LWC and droplet sizes found during encounters with clear icing do fall within the ranges of the envelope. One concern is, however, that the envelope specifies combinations of LWC, droplet size and altitude which may never occur in nature (Horne 1981).

Rime icing is prevalent in supercooled stratiform clouds. The ranges specified in FAR Part 25, Appendix C are median droplet sizes from 15 to 40 μm and liquid water content from 0.2 to 0.8 g m^{-3}. The specified temperatures are the same as those for clear ice. Rime ice is generally acknowledged to form at much lower temperatures than clear ice, sometimes as low as the -22°C specified by the envelope. Recent studies (Jeck 1980, Glass and Grantham 1981, Bain and Gayet 1982, Gayet and Bain 1982) report that median effective droplet sizes are less than 20 μm for rime ice. Jeck (1983) further reports that droplet median volume diameters cluster around 10 to 15 μm and thus are outside the envelope for layer

clouds below 10,000 ft. Icing is usually restricted to a 3000- to 4000-ft layer in stratiform clouds.

From the above discussion, it is obvious that there is considerable overlap in the ranges of physical parameters causing the two types of icing. It is this overlap that results in the occurrence of both types simultaneously -- called mixed icing. Therefore, both types of icing may occur under the same range of conditions, making an exact distinction between rime and clear ice based on liquid water content, droplet size and temperature impossible under certain circumstances. More research is necessary to at least attempt to refine the ranges of clear and rime ice occurrence. But this may be in vain until liquid water content and droplet size distribution can be measured on at least the same routine basis and scale as are temperature and humidity. Rime is without doubt the most prevalent of the two types. An early study (Perkins et al. 1957) of Air Force reconnaissance flights at the 700- and 500-mb levels reports that rime occurred during 72% of the icing encounters and clear ice during only 10%. Mixed icing occurred during 17% of the encounters, thus being more common than clear ice alone.

Clouds that produce icing are often found in conjunction with frontal situations. Smyth (1952) estimated that 85% of reported icing cases occurred during the passage of warm fronts, cold fronts or occluded fronts. Stratus clouds associated with a warm front are most conducive to rime icing. The cumuliform clouds frequently found along the leading edge of a cold front may contain conditions appropriate for clear ice formation. Occluded fronts have the characteristics of both warm and cold fronts; thus both icing forms may be found. In addition, occluded and warm fronts often produce freezing precipitation, a very severe icing situation. Virtually any degree of severity or type of icing may be associated with any type of front, however. Furthermore, icing need not be restricted to frontal situations -- it may be found in any type of airmass cloud at below-freezing temperatures. The point to be made is that since more cloudiness is associated with frontal boundaries and low pressure systems, icing is certainly more predominant in these situations.

Another major consideration is the topography. The intense orographic lifting found over mountains can support large concentrations of heavy supercooled droplets. The combination of a frontal situation and terrain-induced lifting produces especially hazardous icing conditions and has been responsible for many aviation mishaps. Also, clouds forming in the lee of large bodies of water

(i.e. the Great Lakes) as a result of the rapid saturation of cold, dry air are particularly apt to produce icing.

Icing may occur during any season. Obviously, in the mid-latitudes it will be more prevalent during winter when the temperature of the lower atmosphere is below freezing. Cyclonic storms and frontal situations with their associated cloudiness are also more frequent during winter. Studies of the probability of encountering icing in the Northern Hemisphere have been conducted by Katz (1967) and Heath and Cantrell (1972). Probabilities were calculated for each month for different flight levels. Both studies utilized temperature and cloud amount, either observed or calculated by dewpoint depression, to construct the probabilities.

There are several situations in which icing is not highly probable in winter stratus clouds. Jeck (1983) reports that winter stratus not associated with strong frontal systems, cyclonic centers or orographic effects is expected to be low in liquid water content because of the low water vapor content of the surrounding cold air and the lack of convection. He also reports that deep stratus associated with snow areas of cyclonic storms has little liquid water because the liquid water droplets evaporate due to a vapor pressure gradient in favor of the snow crystals. The liquid water content is also expected to be very small in the stratus formed by upslope flow in the western edge of cold air outbreaks extending from central Canada into the central plains states.

FORECASTING ICING

As mentioned previously, the National Weather Service (NWS) is responsible for preparing icing forecasts for the civilian sector. In the Department of Defense, the U.S. Air Force Air Weather Service (AWS) and the Naval Weather Service both forecast icing. The AWS is also responsible for forecasting for the Army. The basic difference between military and civilian icing forecasting doctrines is that military forecasts tend to be oriented toward a particular flight mission while the NWS issues routine regional forecasts. To obtain a briefing for a civilian flight one should contact an FAA Flight Service Station (FSS) although NWS Offices do provide briefings on request. A qualified briefer will _interpret_ the NWS products applicable to the route of flight. Because the Navy generally applies techniques used either by the NWS or AWS in forecasting icing, its methods will not be discussed here. It suffices to say that most of the rules and techniques listed in the Navy _Aerographer's Mate 1 & C_ (NAVETRA 1974) are those listed in the AWS _Forecaster's Guide on Aircraft Icing_ (AWS/TR-

80/001). What will be described here are products and techniques generally applied by the NWS and AWS to produce an icing forecast. In addition, a discussion of the techniques described in the AWS/TR-80/001 will be presented, it being the definitive document on icing forecasting in both the military and civilian communities.

FORECASTS BY THE NWS

NWS icing forecasts are contained in the Aviation Area Forecasts (FA) prepared by the NWS National Aviation Advisory Unit in Kansas City, Missouri. The unit prepares and issues six regional FA's for the conterminous U.S. land and adjacent coastal waters three times daily, with updates whenever Sigmets or Airmets are issued. Prior to November 1982 they had been prepared by Area Forecast Offices located throughout the country. Potential icing conditions are routinely included in these forecasts, an example of which is shown in Figure 1. The forecast for icing or no icing is valid for 12 hours, but more precise times and locations of anticipated icing are usually included in the forecast. In addition to the area forecast, Sigmets and Airmets, advisories relating to significant weather phenomena, are issued for icing when hazardous situations arise. Sigmets cover the most severe phenomena and are normally stimulated only by pilot reports (Pireps) of icing encounters.

The National Meteorological Center (NMC), where most NWS forecast guidance and aids (analyses, model predictions, etc.) originate, issues no explicit icing information products for the conterminous U.S. land areas. Nor within the NWS aside from Air Force technical papers, are there any definitive instructions for preparing an icing forecast. To produce a reasonable icing forecast the function of the forecaster responsible for the area forecast is to assimilate applicable products and extract pertinent information from the numerous NMC guidance forecasts available, Pireps, satellite imagery, radar observations, upper air soundings and locally analyzed data. The accuracy of this forecast then is dependent upon the experience of the forecaster, receipt of Pireps and the accuracy and interpretation of computer and manually derived forecasts and models. Obviously, the forecaster must look at many aspects of the atmosphere in preparing a forecast.

The basic steps taken are to establish the forecast freezing level and the presence of moisture. Obviously, sufficient moisture at altitudes above the freezing level presents a potential icing situation. After the areas of probable icing have been defined, the forecaster then carries out a more detailed analy-

BOS FA 161240
KAUS KBOS 161240
161300-170700
OTLK 170700-171900

NEW ENG NY PA ADJ LE LO NJ CSTL WTRS...

HGTS MSL UNLESS NOTED...

TSTMS IMPLY PSBL SVR OR GTR TURBC..SVR ICG..AND LOW-LVL WIND SHEAR...

FLT PRCTNS...
FOR CIG AND VSBY BLO 10 AND 3 IN ST SNW R AND ZR OVR ALL BUT SE AND NW ME BUT WL SPRD INTO THIS AREA BTN 13Z AND 18Z.

FOR OCNL MDT TURBC BLO 160 AND FQT MDT BLO 90 OVR LE LO PA NJ NY ADJ CSTL WTRS SPRDG NE OVR ERN NEW ENG ME ADJ CSTL WTRS BY 18Z.

FOR PSBL LOW LVL WND-SHEAR WITHIN 50 NM LOW PRES CNTR AND TROUGH N OF THE LOW.

FOR OCNL SVR ICGICIP IN MXD PCPN AREAS OVER ERN AND CNTRL PA NJ SERN NY SRN NEW ENG ADJ CSTL WTRS. ICG WL GRDLY DMSH TO MDT BHND LOW. OTRW FQT MDT MXD ICGICIP OVR ENTR FA AREA.

SYNS...
LOW PRES OVR SERN PA AT 13Z WL MOV OFF THE NJ CST ARND 15Z AND THEN INTSFY RPDLY AS IT MOVES NEWD OVR CAPE COD ARND 22Z AND THRU THE GULF OF ME BTN 23Z AND 05Z.

SIGCLD AND WX...
CNTRL AND ERN PA NJ CNTRL AND ERN NY NEW ENG ADJ CSTL WTRS
100 SCT OVR SE AND NW ME. OTRW CIGS AND VSBYS VRBL AT OR BLO 1 THSD AND 3 MI IN SNW SPRDG NE THRUT ME BY 18Z. HIR TRRN OBSCD. TOPS LYRD TO 200. SNW WL OCNLY MX WITH SLT OR ZR OVR INTR MA INTR CT SERN NY NW NJ NERN AND CNTRL PA. SNW WL CHG TO OR MX WITH R OR SLT OR ZR OVR CSTL MA RI CSTL NY SERN PA NJ ADJ CSTL WTRS. CONDS WL GRDLY IPV OVR SERN PA SRN NJ BCMG BY 00Z 20 BKN WITH CHC VSBY LCLY BLO 3 MI IN SCT SNWSHWRS. THESE CONDS WL SPRD NEWD THRUT ALL BUT CNTRL AND NERN NY VT AND NRN ME ADJ CSTL WTRS BY 07Z. OTLK BCMG VFR WND XCP MVFR CIG SW OF ERN AND CNTRL NY VT NRN VT NRN ME.

WRN PA WRN NY LE LO
CIGS AND VSBYS VRBL AT OR BLO 1 THSD FT AND 3 MI IN SNWSHWRS. HIR TRRN OBSCD. TOPS LYRD TO 90. CONDS WL IPV BTN 21Z AND 00Z TO 25 BKN WITH CHC 10 BKN 3SW-. OTLK...MVFR CIG SW.

ICG AND FRZLVL...OCNL SVR ICGICIP OVR MXD PCPN AREAS OF SRN AND NERN PA NJ SERN NY SRN NEW ENG ADJ CSTL WTRS GRDLY DMSHG TO MDT ABT 100 NM BHND THE LOW. OTRW FQT MDT RIME ICGICIP OVR ENTR FA AREA. FRZLVL SFC NRN NEW ENG WRN NY WRN PA RSG TO 60 SERN NJ. FRZLVL WL LWR TO SFC OVR ENTR AREA BY 07Z.

TURBC...OCNL MDT TURBC BLO 160 AND FQT MDT WITH CHC SVR BLO 90 OVR LE LO PA NJ NY ADJ CSTL WTRS SPRDG NE OVR NEW ENG ADJ CSTL WTRS BY 18Z.

THIS FA INCORPORATES THE FOLLOWING AIRMETS STILL IN EFFECT...
YANKEE 2.
DAD

Icing Translation

Icing and Freezing Level...Occasional severe icing in clouds and in precipitation over mixed precipitation areas of southern and northeastern Pennsylvania, New Jersey, southeastern New York, southern New England and adjacent coastal waters gradually diminishing to moderate about 100 nautical miles behind the low. Otherwise frequent moderate rime icing in clouds and in precipitation over the entire forecast area. Freezing level at the surface over northern New England, western New York, western Pennsylvania rising to 6000 ft over southeastern New Jersey. Freezing level will lower to the surface over the entire area by 0700Z.

Figure 1. NWS area forecast. Solid lines enclose the potential icing forecast.

sis, applying empirically derived rules to establish the likely intensity of the icing.

The current synoptic situation dictates the degree of additional analysis required to produce the icing forecast. Of particular interest are the existence and intensity of fronts and low pressure systems and the associated cloudiness and precipitation patterns approaching the region. If an area will be under the influence of a large, dry high pressure system, or if the lower atmosphere will be above freezing, there is little need to prepare an icing forecast except under special circumstances.

The locations of forecast freezing levels are established using several prognostic products. Probably the most useful is the Low Level Significant Aviation Weather Prognosis (Fig. 2). This particular facsimile product is manually prepared using other analyses and numerical forecast products. The chart is valid at 6 to 12 hour intervals out to 48 hours, forecasting significant weather between the surface and the 400-mb level. Normally displayed are surface precipitation and type, surface pressure, location of fronts, lows and highs, cloud ceilings, with bases at or below 3000 ft above ground level, turbulence areas, and the height of the freezing levels. Freezing levels are given at 4000-ft altitude intervals, but can be interpolated for more precision although they are only forecast for about the first 18 hours of the forecast chart series. This product is especially useful for icing forecasts because it displays much of the prognostic situation in addition to the freezing levels. A rough estimate of potential icing can be implied from clouds located above the freezing level shown on this product.

The 850-mb Limited Area Fine Mesh (LFM) model prediction is also useful for determining upper air temperature patterns. This facsimile product (Fig. 3) predicts heights and temperatures at the 850-mb level (approximately 5000 ft) for 12-hour intervals out to 48 hours. Comparing the 0°C contour at this level with freezing levels predicted by the Low Level Significant Aviation Weather Prognosis gives a reasonable idea of lower atmosphere temperature patterns. Further useful information can be obtained by examining the LFM 1000- to 500-mb thickness prognosis (Fig. 4). The thickness of this layer (the 500-mb level altitude is at approximately 18,000 ft) is a primary indicator of the temperature in the layer, and it is within this layer that icing is most likely. The location of the 5400-m thickness contour is usually in close agreement with the location of the 850-mb 0°C contour. A generally accepted rule-of-thumb is that the 5400-m thickness contour indicates the changeover from rain to snow on the surface if precip-

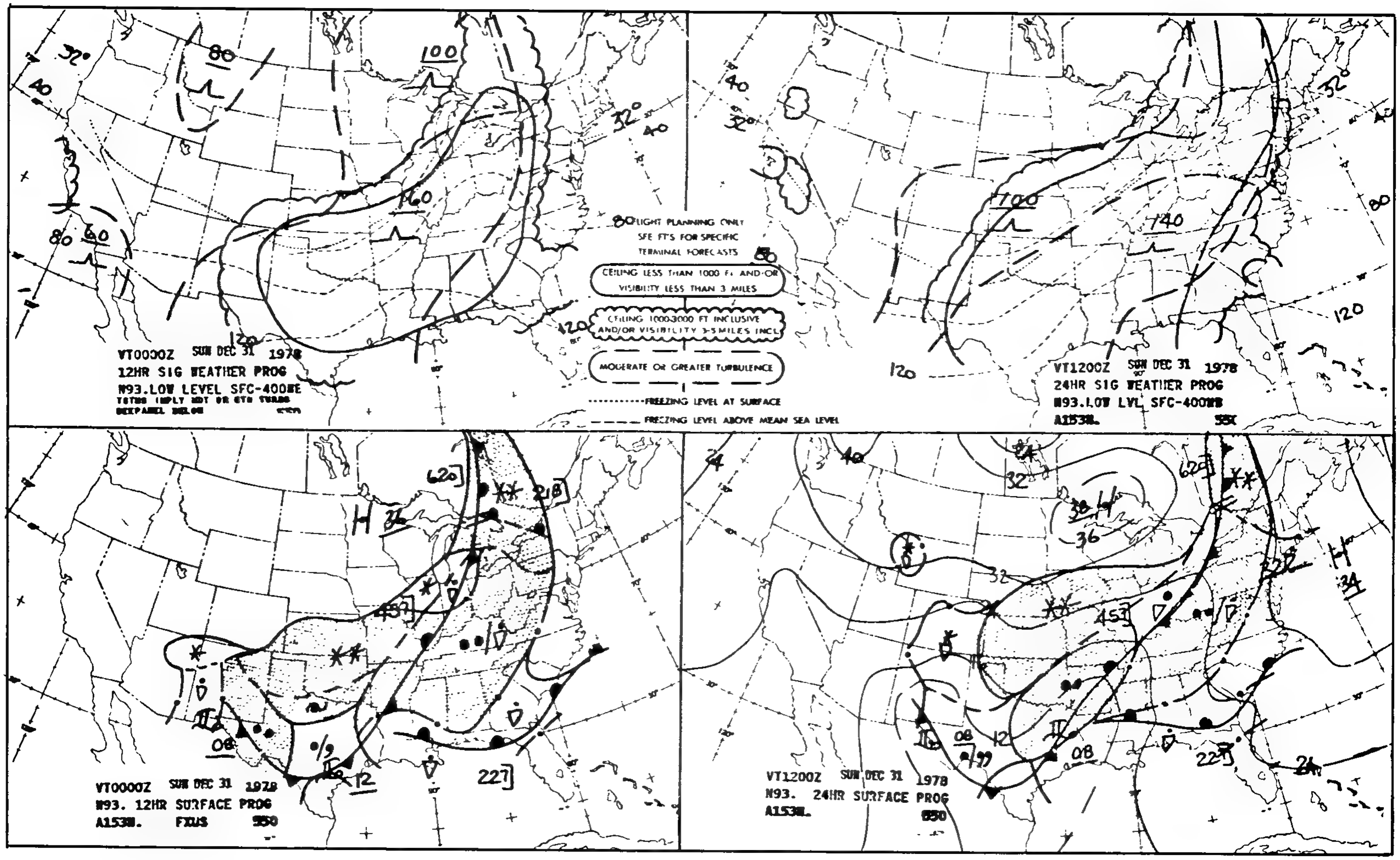
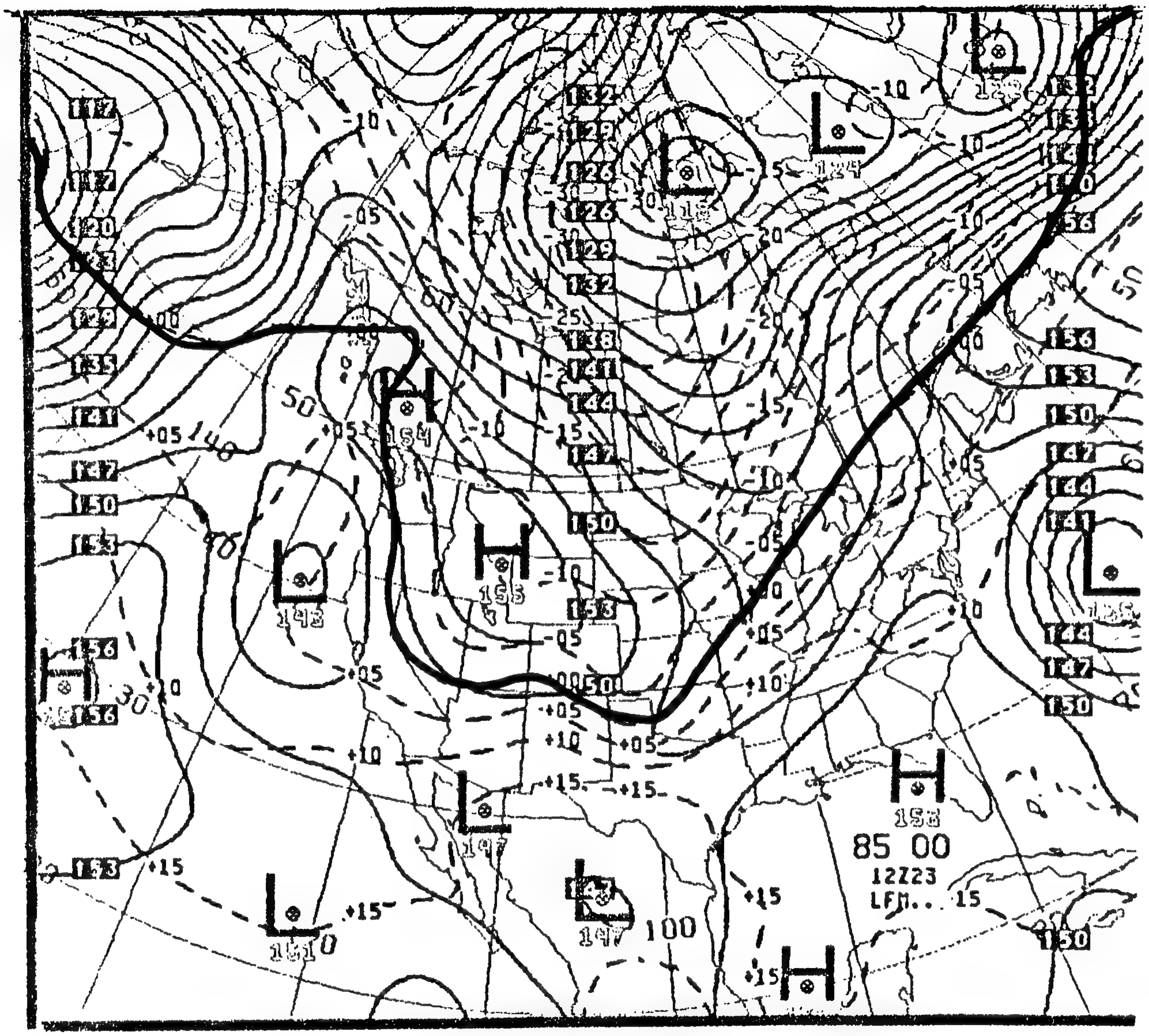
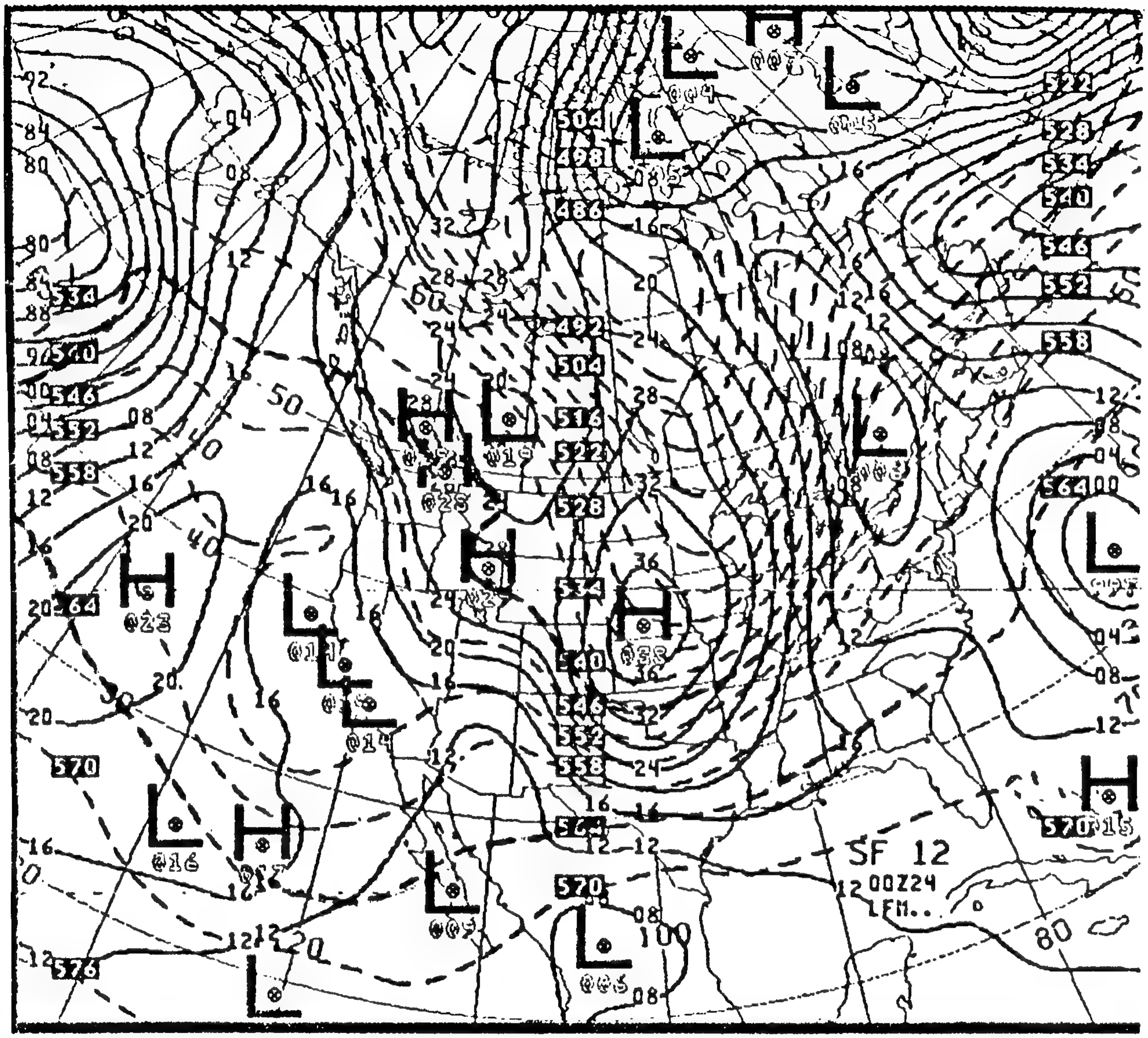


Figure 2. The low-level significant aviation weather prognosis.



D170 .. 850MB ANALYSIS HEIGHTS/TEMPERATURE 12Z TUE 23 NOV 1982

Figure 3. LFM 850-mb height and temperature analysis.



0177 .. 12HR FCST MSL PRES/1000-500 THK VALID 00Z WED 24 NOV 1982

Figure 4. LFM surface and 1000-500 mb thickness prognosis.

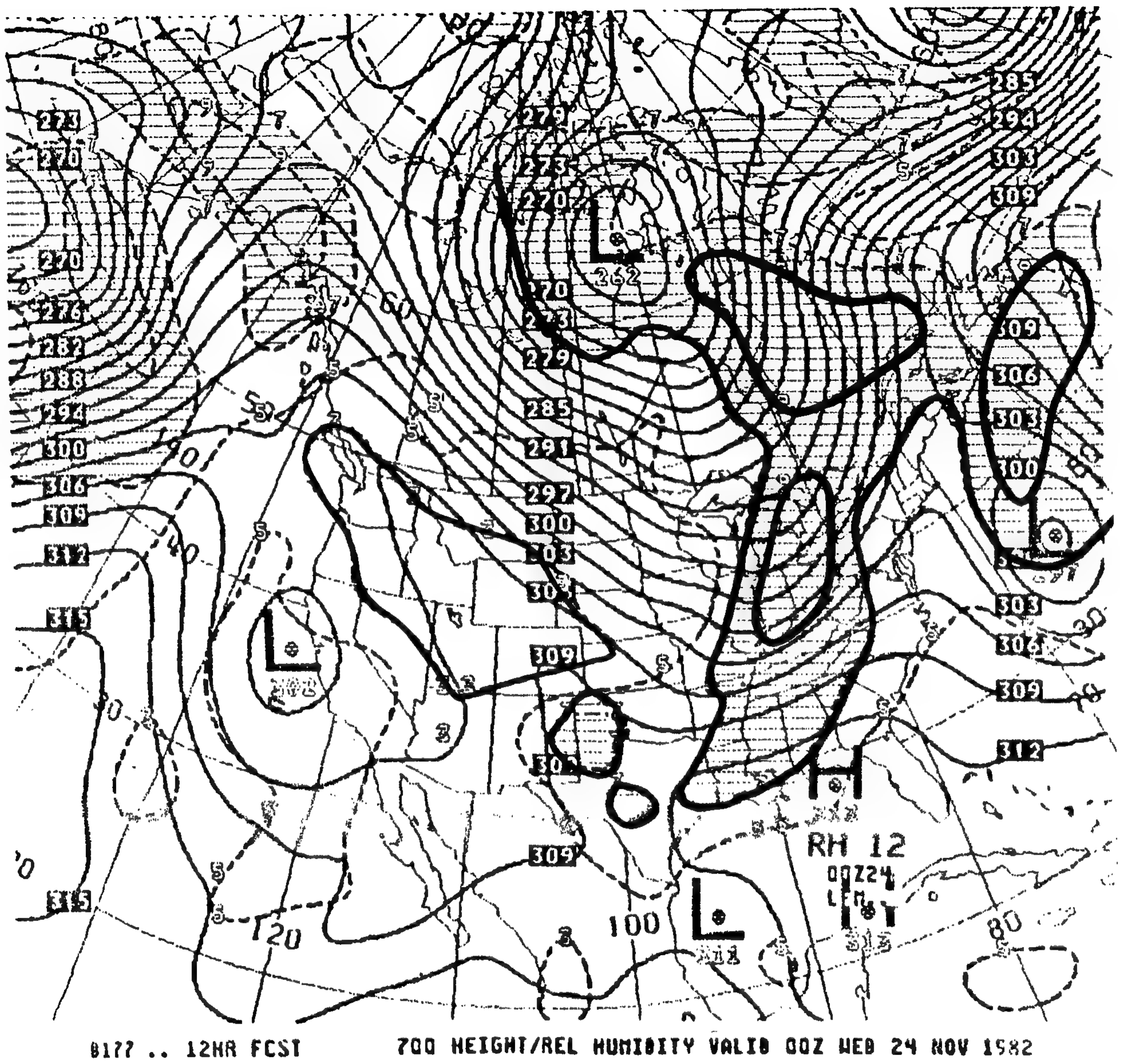


Figure 5. LFM 700-mb height and relative humidity prognosis.

itation is present. An area of moderate to severe icing aloft is generally found immediately on the cold side of this boundary.

In addition to lower atmosphere freezing levels, minimum temperatures in areas of suspected icing need to be examined. The type and severity of icing are quite dependent upon temperature, with very low temperatures generally corresponding to lighter rime icing potential. A variety of other products, including both prognostic and current analysis charts, are used for this purpose.

The forecast moisture distribution is examined using relative humidity prognoses, primarily from the LFM forecast. One of the primary products for this is the 700-mb LFM prognosis (Fig. 5), which gives the average relative humidity from the surface to about the 450-mb level, covering that layer of the lower atmosphere where icing is most likely to exist. Rules-of-thumb state that 90% relative humidity indicates steady surface precipitation, while 70% indicates showers. Both would be indicative of clouds in this layer.

Another important aid, used to refine locations of moisture, is a numerical teletype product, the FOUS60 through 72 series (Fig. 6), which gives forecast moisture aloft over selected stations. The FOUS60-72 is produced by vertical and horizontal interpolation of the LFM output products. Relative humidities are given for three levels: the boundary layer (1000 to 950 mb, which is useful in forecasting low stratus clouds), an intermediate layer extending from 950 to 720 mb (levels of cumulus and/or low altocumulus), and a third layer extending from 720 to approximately 490 mb (altocumulus to low cirrostratus). In addition to allowing a more accurate determination of area-wide moisture, the FOUS60 enables the forecaster to more closely examine the vertical distribution, potentially allowing a breakdown of the vertical levels where icing may be expected. Another product useful to moisture analysis is the LFM Surface Precipitation and Vertical Motion Prognosis, which delineates areas of expected surface precipitation. As with temperature analysis, other prognostic and analysis products may be used to examine upper level moisture in more detail.

Once the likely occurrence of icing has been established, the intensity and type must be specified. This process is quite subjective and, as mentioned previously, is a matter of the forecaster's ability and experience. Some examples of guidelines used for severity, as obtained from Dave Dilley, National Weather Service Forecaster at Logan Airport in Boston, are briefly outlined here:

Severe icing is generally associated with an area of steady surface precipitation (90% relative humidity at 700 mb) with 850-mb temperatures of 0° to -6°C.

The teletypewriter message has the following format:

```
FOUS72 KWBC 191844
TO CIRCUITS 30 33 34
OUTPUT FROM 12Z NOV 19 80
STA RH R1R2R3  VVLI HHDDFF TBPSPTT
SEA 87 998120  //12 492407 8921///
 06073 987320 -1312 442513 8720000
 12061 976819 -1011 402821 8518001
 18055 965228 00811 372927 8419001
 24064 954678 00519 332729 8316001
 30073 935595 02309 302629 8317001
 36084 927598 01807 262731 8114001
 42092 939192 02708 212629 7914002
 48091 929092 02606 152824 7711004
```

```
CODE:
FOUS72 KWBC YYGGGG
OUTPUT FROM 12Z NOV 19 80
```

```
First line:                    STA RH  R1R2R3  VVLI  HHDDFF  TBPSPTT
                               SEA 87  998120  //12  492407  8921///
```

Station: Seattle

Mean Relative Humidity: 87%

Relative Humidity (layer 1): 99%

Relative Humidity (layer 2): 81%

Relative Humidity (layer 3): 20%

Vertical Velocity (700mb):not possible to compute

Lifted Index: 12

1000-500 mb thickness: 549 decameters

Boundary Layer Wind Direction & Speed: 240°/07 kt

Boundary Layer Temperature: 289 K

Sea Level Pressure: 1021mb

6-hr Accumulated Precipitation: not given for initial conditions

Third line which is 12-hour forecast:

```
TT RH  R1R2R3  VVLI  HHDDFF  TBPSPTT
12061  978119  -1011 402821  8518001
```

Forecast Projection (hours)

Mean Relative Humidity: 61%

Relative Humidity (layer 1): 97%

Relative Humidity (layer 2): 81%

Relative Humidity (layer 3): 19%

Vertical Velocity (700mb):-1.0 microbar/sec

Lifted Index: 11

1000-500 mb thickness: 540 decameters

Boundary Layer Wind Direction & Speed: 280°/21 kt

Boundary Layer Temperature: 285 K

Sea Level Pressure: 1018 mb

6-hr Accumulated Precipitation: .01 inches

Figure 6. The FOUS60-72 moisture aloft forecast.

Freezing rain also indicates severe icing. Most severe icing occurs below 8000 ft.

Moderate or moderate to severe icing can be expected in areas of rain or snow showers, indicated by 70% relative humidity on the 700-mb LFM prognosis. Accompanying temperatures range from 0° to −10°C. Moderate icing normally occurs below 12,000 ft, occasionally reaching higher altitudes.

Light icing occurs with 60% to 70% relative humidity and lower temperatures, −10° to −15°C. Light icing conditions would also be expected to reach higher levels.

Most forecasts call for mixed or rime ice. Clear icing conditions are rarely forecast, one exception being during a severe freezing rain situation. Generally, moderate to severe icing will be classified as rime or mixed, while light will normally be classified as rime only.

The forecast synoptic situation combined with possible terrain or local effects is also very important to the area icing forecast. For instance, under a cold, dry westerly flow, moderate to severe icing may be expected up to 100 miles east of the Great Lakes with temperatures as low as −14°C. Over mountainous areas, what would be light or moderate icing conditions elsewhere may become severe due to intense orographic lifting. These examples emphasize the need for an experienced forecaster who realizes the importance of local effects that will not be evident in any standard product issued by the NMC.

The preparation of Sigmets concerning icing is primarily a "nowcast" situation. These advisories are normally stimulated by Pireps of an actual icing situation. The forecast may then be updated by projecting icing areas forward in time if the forecaster believes that the icing situation will remain. Usually the Sigmet is canceled after three hours if no further Pireps are received. Although Pireps tend to be sporadic, they are most often received from high-traffic areas where they are of most use to other aircraft.

The forecasting guidelines described above are certainly not followed by all forecasters the NWS. The intent has been to present examples of how the procedure may be carried out. The AWS Forecasters' Guide on Aircraft Icing (AWS/TR-80/001) is generally available to NWS forecasters. While many empirical rules and techniques are listed in it, several are quite sophisticated, requiring the manipulation of upper-air soundings. The NWS forecaster has little time to use such methods. The icing forecast is only a small part of the area forecast, and the forecaster has other duties, so only a small amount of time can be

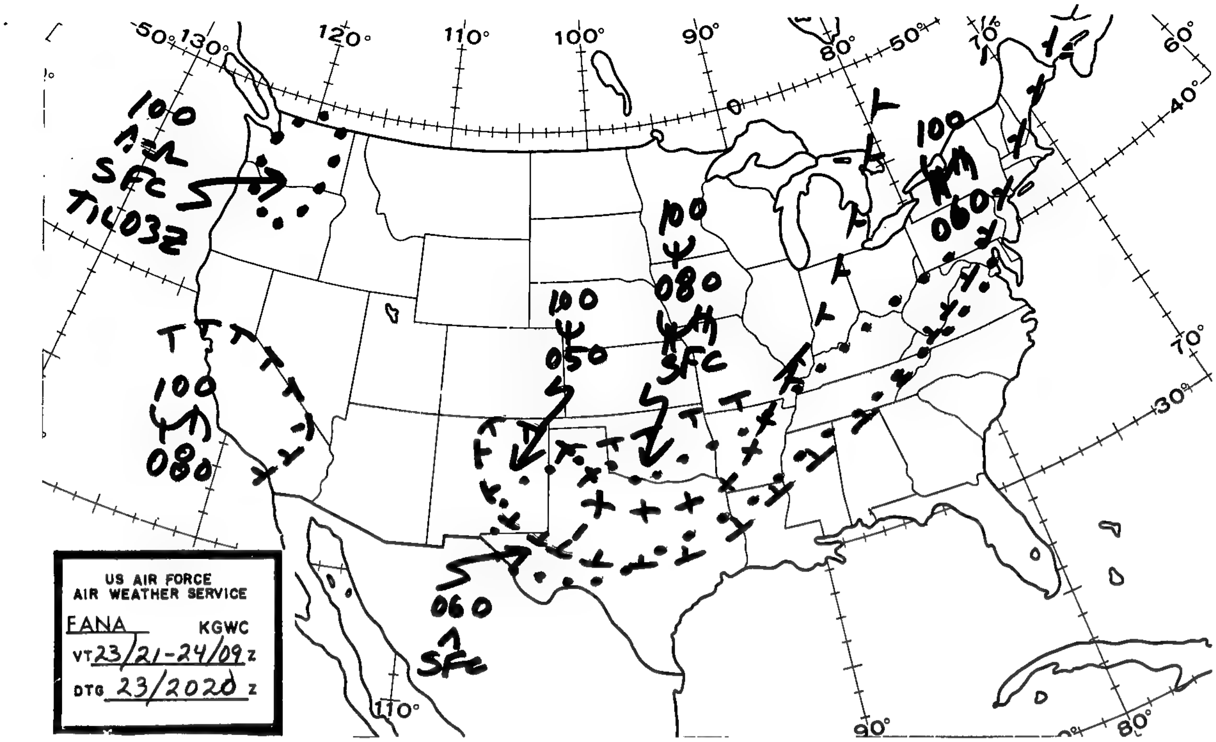


Figure 7. AFGWC FANA icing and turbulence forecast.

devoted to icing. Therefore, the icing forecast is generally based upon the forecaster's own knowledge of icing.

FORECASTS BY THE AWS

AWS detachments forecast on a mission/request basis. There is no Air Force product comparable to the Area Forecast produced by the NWS. Pilots obtain briefings from qualified detachment forecasters who make use of a variety of NMC and Air Force Global Weather Central (AFGWC) products to produce the mission forecast. In contrast to the NMC, the AFGWC issues specific icing products which are heavily relied upon by AWS detachments for the icing forecast.

The FANA and FANH facsimile charts depict areas of potential icing and turbulence for 12-hour time periods. FANA (Fig. 7) covers the contiguous United States, depicting low-level icing and turbulence from the surface to 10,000 ft. FANH shows this information for higher altitudes, 10,000 to 55,000 ft, and covers most of the Northern Hemisphere. Both charts are generally produced twice daily.

The transmitted FANA and FANH charts are manually produced following a rigorous procedure (AWS WF 105-434, 105-435). Several "stacks" of products are constructed in which features from various NMC and AFGWC products relevant to icing are transferred to transparent overlays. The products used are those which

show present and forecast temperature, dewpoint depression, vorticity advection, thermal advection, vertical velocity, the location of fronts, highs, lows, troughs and thunderstorms, cloud coverage, visibility, Sigmets and Pireps. In addition, explicit numerical products showing the locations of clouds, freezing levels and icing are key elements in the production cycle. The various overlays of relevant meteorological parameters are integrated and compared to the numerical/icing products. These procedures are geared to checking the numerical icing products against present and forecast conditions to ensure that conditions (i.e. moisture and temperature) are conducive to icing, and to point out other areas of potential icing that may not be included in the icing products. Rules listed in AWS/TR-80-001 are generally applied by the forecaster. What results from this multi-generation production cycle is an integrated picture of icing conditions in which continuity exists both in time and space (horizontal and vertical) from which the FANA and FANH are produced.

There are two independent types of numerical icing products used in the production cycle. One automatically examines past and forecast radiosonde reports, applying rules for the prediction of icing conditions from radiosondes as outlined in AWS/TR-80/001, which are discussed later. The other uses the AFGWC five-layer cloud model supplemented by satellite data, presumably searching for areas of clouds, then checking other forecast model output fields for below-freezing temperatures in those areas where sufficient clouds are predicted. The type and severity of icing is again forecast by the automatic application of rules given in AWS/TR-80/001. While playing a key role in the production of the FANA and FANH, these are strictly internal production aids and are not available to the weather station forecaster.

The FANA and FANH charts are used as primary guidance for preparing a specific mission icing forecast by an AWS detachment. Since they are valid for long (12-hour) periods, the briefer must use other aids to determine if the icing potential still exists. One rapid check is to assess whether clouds still exist in the area of predicted icing. This is best accomplished with recent satellite imagery and NWS facsimile issued Weather Depiction Charts. The forecast is corrected for advection effects in this manner. Another common practice in AWS detachments is to delineate areas of less than 5°C dewpoint depression on upper air charts (850, 700 and 500 mb). This rapidly outlines areas where clouds are likely to exist or form. The Low Level Significant Aviation Weather Prognosis (Fig. 2) is also used as an aid to assess the validity or currency of the FANA or FANH.

For the local area, where aircraft will be ascending and descending, more detail is applied to the icing forecast. Generally a sounding from an upwind location is examined for potential icing by considering temperature and dewpoint depression. A popular technique that is applied to the sounding to accomplish this, called the Minus 8D method, is discussed later in this report. The icing depicted by the upwind sounding is indicative of future conditions at the location of interest. The FOUS60 moisture-aloft forecast is also useful to establish future icing potential near the station. This is used in essentially the same manner as by the NWS area forecast offices. Combining the FOUS60 forecast with predicted freezing levels aloft provides a reasonable picture of future icing potential at a particular location.

AWS detachments that support Army helicopter units usually prepare forecasts for a particular operational area, rather than for long routes of flight. Once again, the FANA is heavily relied upon for low level (< 10,000 ft) guidance. In this case, however, several soundings at sites surrounding the operational area may be used for a more detailed forecast. The Minus 8D method, as well as other rules listed in AWS/TR-80/001, may be applied to the soundings to evaluate the icing potential. Again the idea is to examine soundings upwind of the operational area to ascertain what conditions may be advected into the area. Other aids as described above are also applied. It appears that somewhat more detail is given to these icing forecasts because the support detachments are responsible for a more limited area and because helicopters are extremely vulnerable to icing.

As is the case with the NWS forecasters, it seems that the more detailed techniques for examining soundings described in AWS/TR-80/001 are too time-consuming to be applied by AWS detachments. Because of manpower limitations little time can be devoted to a detailed icing forecast. Likewise, the detail and accuracy of the forecast are largely a function of the experience and ability of the forecaster.

FORECASTING ICING AS OUTLINED BY AWS/TR-80/001

Because AWS/TR-80/001, Forecasters' Guide on Aircraft Icing, is the definitive forecasting document in both the military and civilian sectors, the techniques described in it will be briefly discussed. This manual is essentially a reprint of Air Weather Service Manual AWSM 105-39 of 7 January 1969, with a few changes. The manual, then, is a synopsis of techniques developed during the

fifties and sixties when much of the research related to aircraft icing took place. Statistics on icing encounters, icing climatology, and even such details as the effects of aerodynamic heating are included in it. Presented here, however, is a synthesis of the procedures utilized to produce an icing forecast, in addition to a physical interpretation of them. Three basic methods are described; the forecaster presumably chooses a method which suits the time and amount of data he has available. Alternatives for forecasting when very little data are available are also suggested.

Preliminary investigations to be made include the determination and prognosis of clouds, temperatures and areas of precipitation along the proposed flight path. Suggested sources for determining clouds (type and vertical extent) are surface observations, radiosonde reports (from dewpoint depression), surface and upper air charts, synoptic models (of frontal structure, etc.), and pilot reports. Local effects such as terrain are also to be considered. Although not specifically mentioned, it is presumed that satellite imagery is now very useful for cloud determination. Areas of below-freezing temperatures are to be assessed from analyzed and prognostic charts, radiosonde reports, and reconnaissance reports, or extrapolated from surface temperatures. Surface reports and charts are to be examined for current precipitation, and forecasts of future precipitation are to be prepared. The AFGWC icing forecasts, FANA and FANH, should be examined to begin the forecast.

The potential for icing along the flight path should be established by this preliminary analysis. What is then necessary is to define the type and severity. The forecaster chooses one of the following methods to determine this based on the available time and data. All methods assume this prior knowledge of clouds, temperatures and precipitation.

Method 1

This method is the most time-consuming and requires the most detailed data, but presumably results in the most accurate forecast. It entails the examination of upwind or prognostic soundings representative of the potential icing areas determined in the preliminary analysis.

Initially, the type of icing is determined by the temperature lapse rate (γ) on the sounding in the cloud layers (small dewpoint depression). Stable layers ($\gamma < \gamma sat$) are assumed to represent stratiform clouds, and thus rime icing. Conditionally unstable layers ($\gamma dry > \gamma > \gamma sat$) represent cumuliform clouds and clear icing. Once the type of icing has been determined for the flight level, an overlay is used to depict its severity. The overlay, a reduced version of which

Table II. Relationship of icing intensity to liquid-water content.

Cumuliform clouds Liquid-water content* g/m^3	Icing intensity	Stratiform clouds Liquid-water content† g/m^3
≤ 0.07	Trace	≤ 0.11
0.08 - 0.49	Light	0.12 - 0.68
0.50 - 1.00	Moderate	0.69 - 1.33
> 1.00	Severe	> 1.33

* Assumed droplet diameter 17 micrometers.
† Assumed droplet diameter 14 micrometers.

is shown in Figure 8, is designed for use on the Skew T - Log P sounding plotting chart. This overlay is placed over the sounding and the curves are used to predict the severity of the rime or clear icing. For rime icing, an additional scale is included to verify that liquid water droplets rather than ice crystals are present in the cloud and that icing will occur. This is discussed further under Method 2.

The severity curves depicted on the overlay originate from work done by Lewis (1947) who defined levels of icing intensity based on measured accumulations on a 3-in.-diameter circular cylinder in a 200 mph airstream. He expanded these definitions to produce curves of icing intensity in terms of liquid water content and a mean effective drop diameter for 10,000 ft pressure altitude and 15°F ambient air temperature. This was a common flight level and airspeed for transport aircraft in the late forties and early fifties. With icing intensity quantitatively defined in terms of droplet diameter and liquid water content, intensity could be defined by liquid water content alone if a mean droplet diameter was assumed. The AWS chose drop diameters of 14 μm for stratiform clouds (rime icing) and 17 μm for cumuliform clouds (clear icing), which resulted in liquid water contents for the various intensities as shown in Table II. The curves denoting intensity on the overlay (Fig. 8) presumably represent these liquid water contents. Average liquid water contents for the two types of clouds are reported (Newton 1977) to have been predicted using a cloud model developed by Best (1952). The model entrains outside air of 70% relative humidity at a rate such that the mass of the air in the cloud is doubled in a moist adiabatic

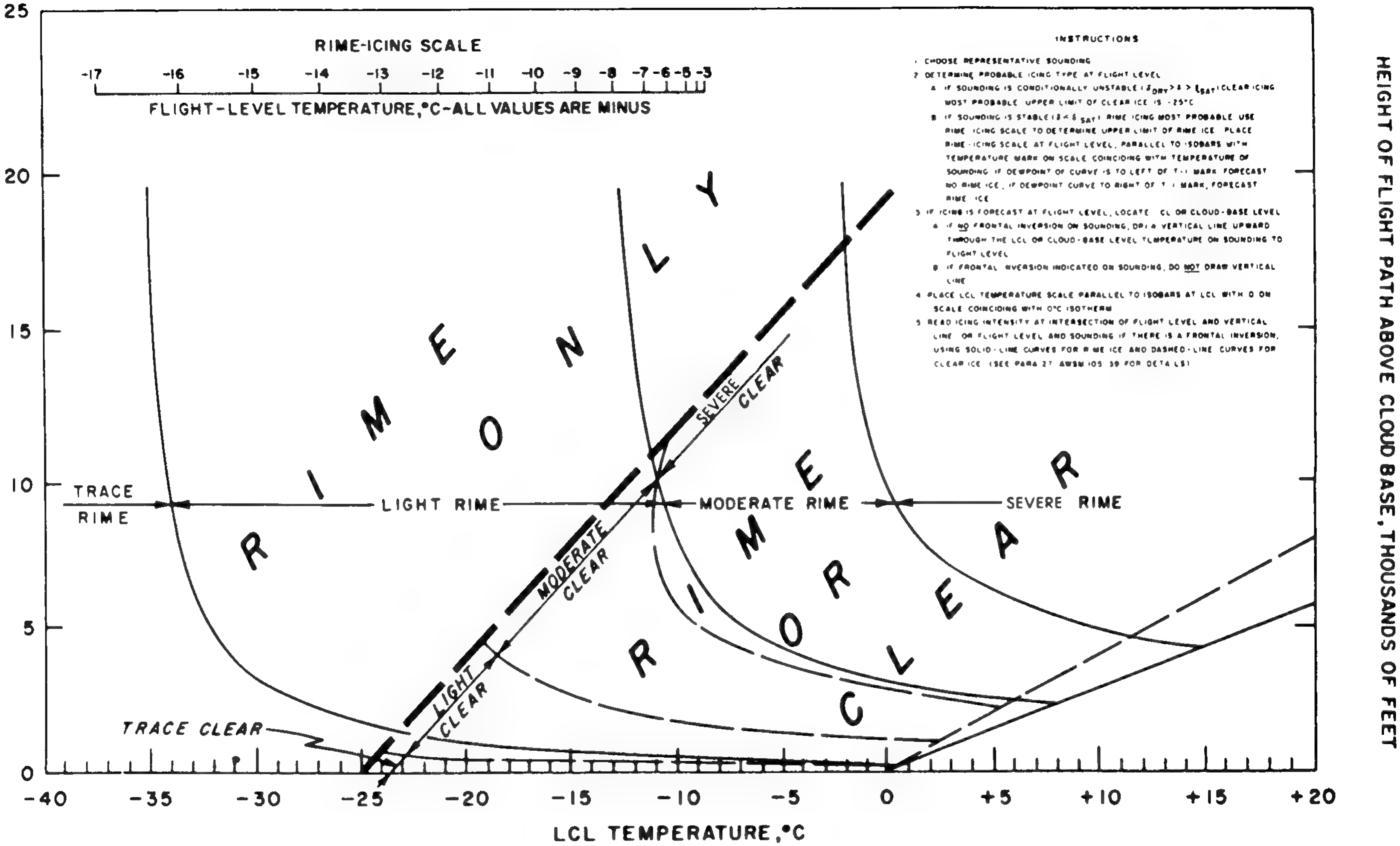


Figure 8. Skew T - Log P overlay for determination of icing intensity (from AWS/TR-80/001).

ascent of 400 mb. Liquid water contents were calculated for various cloud base temperatures and base heights of 950 and 850 mb for cumuliform and stratiform clouds, respectively (Cox 1959). Experimental results indicated that only half of the calculated value should be used for stratiform clouds and the full amount for cumuliform clouds. The curves of constant liquid water content (icing intensity) on the overlay (Fig. 8) were positioned using these model calculations. In essence then, this overlay provides a quantitative method of predicting icing intensity, based on accumulation on the 3-in. cylinder in a 200 mph airstream described above. While the model may require updating, the fact that the intensities are quantitatively produced makes this type of approach very suitable for future study.

Method 2

This method is limited to stratiform clouds and is based upon considerations of the phase of water in the cloud. The forecaster is supposed to resort to this method if time or lack of data prohibits him from using Method 1.

The recommended procedure is to determine the probable phase condition of the particles in the stratiform clouds using frost point considerations. Figure 9 shows a nomogram recommended for this. From the forecasting standpoint, all that is required is to establish the presence of stratiform clouds (from stability or other considerations), then to plot flight level temperatures and dewpoints (obtained from any reasonable source) on the chart. The likelihood of icing is then read directly from the chart.

The nomogram was devised from studies by Appleman (1954) and updated with additional weather reconnaissance data. The technique essentially compares the degree of saturation with respect to both ice and water, as water droplets would be expected to eventually change to ice crystals in a cloud having small vertical velocities. Saturation with respect to ice occurs at higher temperatures than saturation with respect to water. Thus a cloud which is saturated with respect to ice and unsaturated with respect to water would contain only ice crystals, presenting little possibility of icing. Likewise, a circumstance in which saturation with respect to water and supersaturation with respect to ice existed would be expected to produce liquid water droplets, and thus rime icing. Finally, a mixture of ice crystals and supercooled droplets would occur if the cloud was near water saturation and supersaturated with respect to ice.

The various lines on the nomogram approximate the two saturations. The line $T = Td$ represents saturation with respect to water, and $T = T_f \approx 0.9\ Td$ is an approximation of saturation with respect to ice. The line $T = 0.8\ Td$, the so-

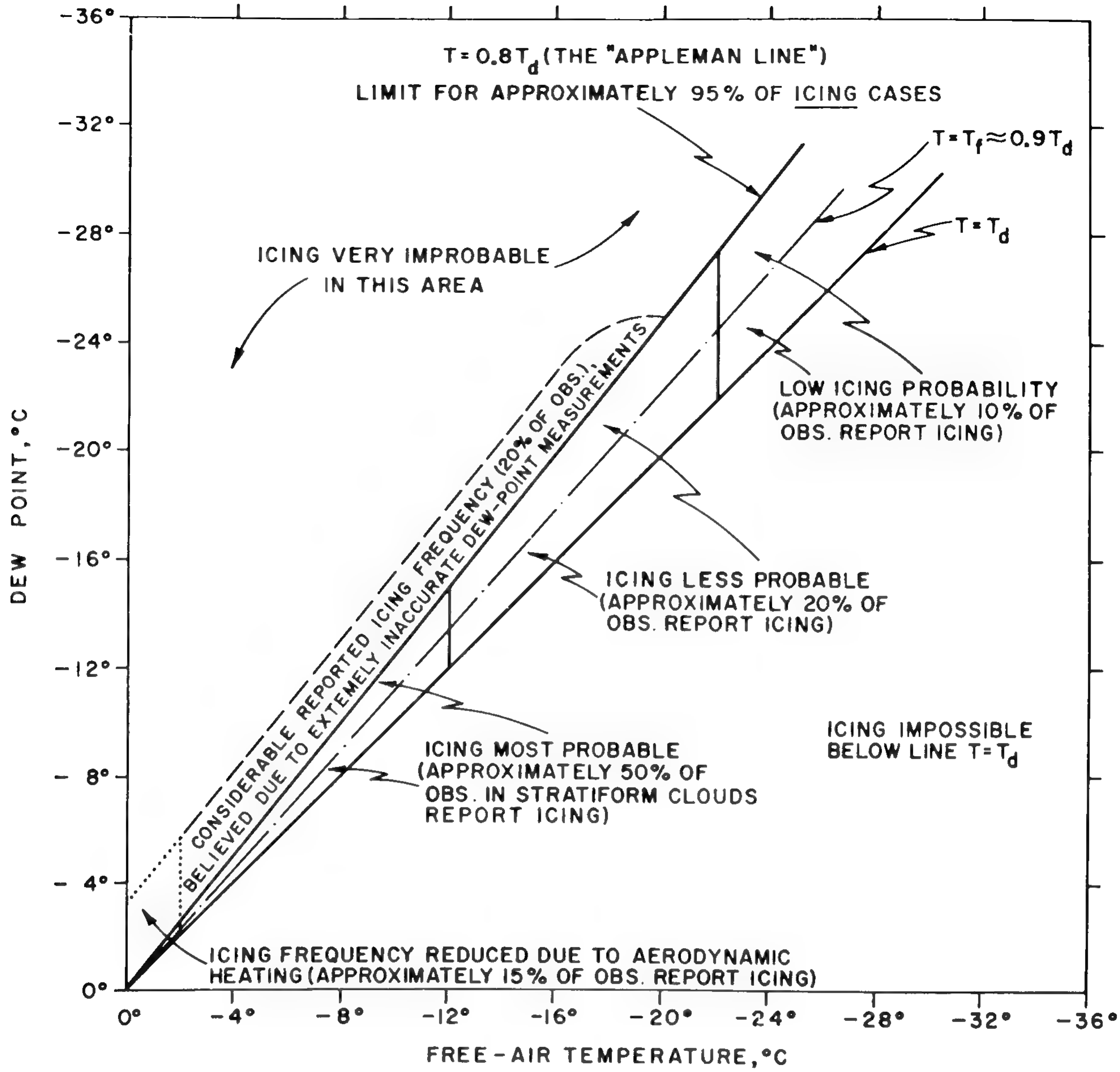


Figure 9. Nomogram for application of frost point technique for rime icing in stratiform clouds (from AWS/TR-80/001).

called "Appleman Line," represents the 95% limit of icing encounters from empirical studies. This line plus the dashed line reflect the fact that reported humidity values in clouds are often inaccurate (most often too low). The vertical divisions represent the likelihood of icing further derived from empirical studies.

The intensity of the icing can only be forecast by climatology in this method. It is advised that the probabilities of encountering trace, light and moderate icing are 87%, 12% and 1%, respectively.

Method 3

The final method recommended by ASW/TR-80/001 consists of using established empirical rules. These can be applied to data that usually are readily available in the weather station. The 12 rules given in AWS/TR-80/001 were reprinted in tabular form in Air Weather Service Pamphlet AWSP 105-56(C1). For the sake of convenience, they are reprinted here as Table III.

Rules 1 and 2 are based upon temperature and dewpoint depression. The type of temperature advection occurring is also considered in the case of rule 2. The data necessary to apply the two rules can be obtained from radiosonde reports and upper air charts. The rules are founded upon empirical studies of dewpoint depression and advection by Thompson (1955) and upon the frost point considerations discussed above after Appleman (1954).

Rules 3-9 are applied using cloud and precipitation information that can be obtained from surface charts. The synoptic situation which produces the clouds (frontal situation, low pressure area, etc.) is also of concern. As with rules 1 and 2, only the intensity of icing can be forecast using these rules.

Rules 10-12 are used to predict the type of icing. These are based solely upon temperature and the type of clouds. Rime is associated with stable stratiform clouds and lower temperatures, while clear is to be predicted for cumulus clouds and higher temperatures. This association has been discussed previously.

Limited Data Forecasting

The manual suggests using empirically derived probabilities when the temperature or the presence of clouds at flight level cannot be established. Figures (not reproduced here) are presented which give the probable frequency of icing as a function of temperature and altitude. A table also predicts the probability of icing as a function of season and flight level. Here no means of predicting the type of icing is given, and the probable climatological frequencies to be forecast for intensities are listed as 87% for trace, 12% for light, and 1% for moderate.

Provisions for making forecasts based on climatological data are also presented. While the general idea is to use them for planning and design studies, they can be used for forecasting for areas where no recent data exist. Briefly, the procedure begins with using published climatologies to obtain the percent frequency of cloud cover and temperature along a given route. Figures are presented from which the percentage of clouds containing icing as a function of temperature may be obtained. The probability of icing is finally arrived at by

Table III. Icing forecasts (extracted from AWS/TR-80/001).

Empirical rules to be used in forecasting aircraft icing are presented. The forecaster can make icing forecasts using either surface or upper air data. Rules assume: 1) Supercooled liquid-water droplets must be present in the flight path. 2) The surface of the aircraft is colder than 0°C.

Icing Intensity Forecasts from Upper Air Data

Check upper air charts and radiosonde reports for temperatures and dewpoint spread at flight level, and the type of temperature advection along the route.

Rule 1*	T	T - Td	Forecast	Probability
a.	0° to -7°C	> 2°C	None	80%
b.	-8° to -15°C	> 3°C	None	80%
c.	-16° to -22°C	> 4°C	None	90%
d.	Lower than -22°C	Any spread	None	90%

Rule 2*	T	T - Td	Advection	Icing forecast	Probability
a.	0° to -7°C	≤ 2°C	Neutral/weak cold air	Trace	75%
			Strong cold air	Light	80%
b.	-8° to -15°C	≤ 3°C	Neutral/weak cold air	Trace	75%
			Strong cold air	Light	80%
c.	0° to -7°C	≤ 2°C			
	-8° to -15°C	≤ 3°C			
	Areas with vigorous cu build-ups due to surface heating			Light	90%

* Icing intensity is defined in terms of its effect upon a reciprocating engine, straight-wing transport aircraft (C-54, C-118). The pilot must refer to the aircraft "dash-one" for recommended actions.

Table III (cont'd).

In-Cloud Icing Intensity Forecasts from Surface Data

If upper air data and charts are not available, check surface charts for locations of cloud shields and precipitation areas.

Rule	Description	Position of clouds	Icing forecast
3	Not due to frontal activity or orographic lifting	Over areas with steady liquid precipitation	Little or none
		Over areas with no liquid precipitation	Light
4	Due to frontal activity or orographic lifting	Presence/absence of precipitation not an indicator.	Indeterminate
5	Up to 300 miles ahead of warm frontal surface position		Light
6	Up to 100 miles behind cold frontal surface position		Moderate
7	Over deep, almost vertical low pressure center		Moderate
8	In freezing drizzle (in or below clouds)		Moderate
9	In freezing rain (in or below clouds)		Severe

Icing Type Forecasts

Rule	Temperature	At or in	Icing type forecast
10	Below -15°C	Flight altitude	Rime
	-1° to -15°C	Stable stratiform clouds	
11	0° to -8°C	Cumuliform clouds and freezing precipitation	Clear
12	-9° to -15°C	Unstable clouds	Mixed (rime and clear)

calculating the product of the percentage of clouds containing icing at the determined temperatures and the climatological percentage of clouds along the route. The manual also notes that climatological probabilities of icing for the Northern Hemisphere have been calculated by Heath and Cantrell (1972).

The Minus 8D Method

Although this technique is not described in AWS/TR-80/001, it is utilized by AWS detachments and will be described here. The method is described in the Navy manual Aerographer's Mate 1 & C, NAVETRA 10362-B, and no reference to its origin is given. With this exception the remainder of the section concerning icing in the Navy manual is a synopsis of discussion, methods and techniques described in AWS/TR-80/001.

This method requires a sounding plotted on a Skew T - Log P chart and is applicable only to rime icing expected in stratiform clouds. The dewpoint depression, D, is calculated for different levels and multiplied by negative eight. This value is also plotted on the sounding chart (called the -8D curve). An icing layer is indicated where the -8D curve is to the right of the temperature curve (-8D value is larger). The intensity of icing is dictated by the size of the area enclosed by the temperature and -8D curves. Further refinement of the forecast is made by considering the cloud type and frost point rules discussed above. The apparent advantage to this technique is that it does not require plotting the temperature and dewpoint values on a separate chart as described under Method 2 above. It does require plotting the -8D curve on the Skew T - Log P sounding chart, however.

This technique is based upon considerations of cloud saturation with respect to ice and water as discussed under Method 2. Supersaturation with respect to ice and saturation with respect to water occur where the temperature curve is less than the -8D curve on the Skew T - Log P chart. The point of intersection is $T = T_f \approx 0.9$ Td as discussed above. While this method avoids plotting values on another chart, it requires calculation and plotting of the -8D curve. This same layer may be determined by using the rime icing scale included on the overlay (Fig. 8) described under Method 1, avoiding any additional plotting.

CONCLUSIONS AND RECOMMENDATIONS

The accuracy of icing forecasts prepared either by the NWS or the AWS depends on the ability and experience of the forecaster. While potential icing may be established by predicting future coincident locations of clouds and sub-

freezing temperatures, accurate prediction of the intensity and type of icing requires skill. One major problem lies with the accepted definitions of intensity as established by the Subcommittee for Aviation Services; the accumulation rate depends on the type of aircraft encountering the icing. Since there is no quantitative basis for the various intensities, there is no rigidly defined scale of intensities that means the same to all forecasters.

All forecasters seem to be limited by the amount of time available to prepare the icing portion of the forecast. There is usually no time to apply sophisticated techniques which may have credence with regard to forecasting ice type and intensity. The forecast is usually the result of the application of the forecaster's working knowledge of icing. It is likely that more accurate forecasts would result if more time could be devoted to their preparation.

The methods and rules-of-thumb described in AWS/TR-80/001 need to be evaluated with regard to accuracy. They were developed from icing data collected in the forties and fifties. These should be updated with more recent data. However, no systematic collection of icing data has taken place in recent years. Only sporadic research flights examining specific aspects of icing or cloud physics have provided recent data. Jeck (1983) has recently assimilated and analyzed reported icing types, intensities and meteorological parameters from the old and recent icing data flights and this large set will be very useful for testing forecasting techiques. A systematic data collection program should be undertaken in which icing intensity should be quantified by measuring accumulation rates on a standard device. A large quantity of such data along with other measurable parameters, namely liquid water content and droplet size distribution, provide a data base capable of enhancing the state-of-the-art of forecasting icing.

A quantitative method of forecasting icing intensity is described in AWS/TR-80/001. The median droplet sizes for stratiform and cumuliform clouds are assumed and intensity is then a function only of liquid water content which has been calculated for various cloud levels using moist adiabatic ascent. Intensities are based on accumulation rates on a 3-in. cylinder in a 200 mph airstream. At this point, it is not known whether or not this model requires updating. The upshot is that a quantitative means of forecasting icing intensity does exist and has been implemented by the AFGWC for use as guidance in preparing the FANA and FANH icing charts. The Navy is also preparing an automatic icing analysis routine for radiosondes to be used at sea (Jeck, pers. comm.). The NWS should

follow suit and implement their own program for providing numerical guidance to the area forecaster. A simpler alternative may be for the NWS to make the AFGWC FANA and FANH charts available to the area forecaster, since the Air Force already puts forth a large effort in the production.

Once a quantitative method of forecasting icing has been accepted, all forecasters should adhere to it. Presumably, the method would relate intensities of icing to accumulation rates on some standard device, say a cylinder of a certain diameter and at a given airspeed. The accumulation rates on all aircraft and the effectiveness of deicing systems could then be related to this standard by both testing and theoretical calculations. This would alleviate some of the confusion that now surrounds the subjective intensity definitions.

Both liquid water content and droplet size distribution need to be measured as part of the standard radiosonde package. These are very important parameters influencing accumulation rate and ice type. Until they are measured on a routine basis and at a reasonable scale, they must be calculated or assumed in prediction models as described above. Standard measurement of these variables would greatly enhance synoptic scale forecasting of potential icing.

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